Indian J. Phys. 77A (6), 587-592 (2003)

AN INTERNATIONAL JOURNAL
IJPA

A model study of gap equation in the heavy fermion superconductors

M S Ojha[1*], G C Rout[2] and S N Behera[3]
[1]S. C. S. (Jr.) College, Puri-752 001, Orissa, India
[2]Condensed Matter Physics Group, Govt. Science College, Chatrapur-761 020, Orissa, India
[3]Institute of Physics, Sachivalaya Marg, Bhubaneswar-751 005, Orissa, India
E-mail : mojha@iopb.res.in

Abstract : The superconducting order parameter due to conduction electrons and the sub-lattice staggered field parameter due to the weakly delocalized *f*-electrons are calculated by Zubarev type Green function method for the heavy fermion magnetic superconductors. We solved the self-consistent mean field equations for the superconducting gap and the staggered field. The mutual influence on each other is studied by varying model parameters of the systems : the superconducting coupling (g_1), antiferromagnetic coupling (g_2), the hybridization (v) for various temperature ranges. The results show a strong correlation between them through the suppression and enhancement of the order parameters and transition temperatures as well as a few anomalous results. This model can explain the strong coupling between magnetism and superconductivity in the UM_2Al_3 and similar U-based systems.

Keywords : Heavy fermion superconductor, narrow band system, local moment in heavy fermions.

PACS Nos. : 74.70.Tx, 71.28.+d, 75.20.Hr

1. Introduction

The field of heavy fermion superconductivity (HFSC) is still the subject of much research activity [1]. We discuss below some properties of the two most recent examples, UM_2Al_3 (M = Ni ; Pd) [2,3] where there exists the homogeneous coexistence between HF superconductivity and local moment magnetic (LMM) order with surprisingly large values of both T_c and μ_s. The U-based HFSC typically show the microscopic coexistence of antiferromagnetism (AFM) and superconductivity at $T \leq T_c \leq T_N$. Both their SC and AFM states exhibit exotic properties. Here, we wish to mention only the discoveries of extremely small staggered moments μ_s = 0.02 μ_B and 0.04 μ_B, along with large commensurate ordering wave vectors for UPt_3 [4] and $UR_{u2}Si_2$ [5] respectively. The homologs UM_2Al_3 (M = Ni, Pd) crystallize in hexagonal structure. The unit cell volume of UNi_2Al_3 is smaller by 4% than that of its Pd counterpart. Consequently, the 5*f*-ligand hybridization is larger in the former. Both compounds exhibit the typical signature of a Kondo lattice. The heavy fermion systems are characterized by a characteristic temperature T^*(called "Kondo lattice temperature") above which the system shows localized character and below which the system exhibits Fermi liquid behaviour. The T^* for the Ni and Pd systems are $\simeq$ 75 K and $\simeq$ 40 K respectively. The hexagonal HFSC UNi_2Al_3 (γ $\simeq$120 mJ/K^2-mole, $T_c \simeq$1K orders antiferromagnetically below $T_N \simeq$ 4.5 K [2]. The HFSC UPd_2Al_3 (γ = 140 mJ/K^2-mole) orders antiferromagnetically with Néel temperature T_N = 14.5 K [3] and the staggered magnetic moment μ_s = 0.85μ_B [6]. The saturated moments are larger than that for UPt_3 and URu_2Si_2 by one to two orders of magnitude. In particular, μ_s = 0:85μ_B is as large as that for ordinary U-based magnets. It is most remarkable that such a large μ_s coexists with HFSC below a T_c. Surprisingly large ordered moments of μ_s are ferromagnetically aligned within the basal planes and antiferromagnetically aligned along the perpendicular directions [6]. Not only AFM but also superconductivity sets at a much higher temperature than Ni-system (T_c = 2 K)

2. Superconducting gap

Very recently Metaki *et al* have observed a magnetic

*Corresponding Author

excitation gap associated with superconductivity in UPd_2Al_3 [7,8] in their neutron scattering experiment. The temperature dependence of the gap is comparable to the one of the superconducting energy gap expected from the weak coupling BCS theory. This energy gap corresponds to $2\Delta(0) = 2.2\ k_BT_c$. It is in same order compared with the weak coupling BCS theory $2\Delta(0) = 3.52\ k_BT_c$. A clear superconducting gap at $2\Delta(0) = 3.8\ k_BT_c$ has been observed in a study of tunneling spectroscopy of UPd_2Al_3 thin film [9]. They also observed that the temperature dependence of this gap, which is obviously a charge gap, is very similar to the one of magnetic excitation gap. The NMR and Knight shift study [10] concludes that *d*-wave pairing is realized in UPd_2Al_3 characterized by a line node of energy gap $2\Delta(0) = 5.5\ k_BT_c$ which is higher than the value $2\Delta(0) = 2.2\ k_BT_c$ [8] and the tunneling spectroscopy ($2\Delta(0) = 3.8\ k_BT_c$).. They conclude saying that it may be due to the anisotropic gap. Recently Rout *et al* have considered a weak coupling BCS type pairing in the Periodic Anderson model to explain the superconducting gap anisotropy [11] and Raman spectra [12] in the non-magnetic heavy fermion superconductor.

3. Theoretical model

Any theoretical model which attempts to explain the observed anomaly in the UM_2Al_3 (M = Ni, Pd) must take into account the simultaneous occurrence of the antiferromagnetic heavy fermion superconducting long range orders. The evidence for the origin of antiferromagnetism (AFM) point towards the more localized 5*f*-states, while the HF superconductivity in the system is due to less localized same 5*f*-electrons. In case when the AFM is due to the same itinerant 5*f*-electorns which are responsible for superconductivity, the former is more likely to be of the form of a spin density wave (SDW) arising form a Fermi surface instability [13]. However, it can be visualized that 5*f*-localized electrons can acquire some itinerant character being hybridized with the conduction electrons of the system. Then superconductivity in these systems can be thought of BCS type phonon mediated weak Cooper pairing in the conduction electrons which exhibits anisotropic *d*-wave type superconductivity [11,12,14,]. In the model presented below, however, the AFM is attributed to a staggered sub-lattice magnetization arising from the 5*f*-delocalized electrons which coexists with superconductivity arising from the conduction electrons. The aim of the present calculation is to assume a simple model in order to investigate the effect of the SC and the AFM coupling constants on the coexistence of AFM and SC in the system. The Hamiltonian of the system is described by

$$\mathcal{H} = \mathcal{H}_c + \mathcal{H}_f^1 + \mathcal{H}_f^2 + \mathcal{H}_h + \mathcal{H}_v + \mathcal{H}_s \tag{1}$$

The uranium(U) site is divided into two sub-lattices 1 and 2 with corresponding creation operators $c^\dagger_{1,i,\sigma}$ and $c^\dagger_{2,i,\sigma}$ respectively of the conduction electrons. The hopping of the conduction electrons between the nearest neighbour sites of the two sub-lattices is described by

$$\mathcal{H}_c = -\sum_{i,j,\sigma} t_{ij}\,(c^\dagger_{1,i,\sigma}\, c_{2,j,\sigma} + h.c.)\,. \tag{2}$$

The Fourier transformed form of $\mathcal{H}_c$ is

$$\mathcal{H}_c = \sum_{k,\sigma} \epsilon_k\ (c^\dagger_{1,k,\sigma}\, c_{2,k,\sigma} + c^\dagger_{2,k,\sigma}\, c_{1,k,\sigma})\,, \tag{3}$$

where $c^\dagger_{1,k,\sigma}$ and $c^\dagger_{2,k,\sigma}$ are the creation operators of electrons belonging to the two sub-lattices 1 and 2 respectively with momentum k and spin σ. The despersion of the charge carriers is ϵ_k which is the Fourier transform of the nearest neighbour hopping matrix element t_{ij}. Similarly the Hamiltonian $\mathcal{H}_f$ describes the intra *f*-electrons in the localized levels corresponding to the flat band,

$$\mathcal{H}_f^1 = \epsilon_f \sum_{k,\sigma} (f^\dagger_{1,k,\sigma}\, f_{1,k,\sigma} + f^\dagger_{2,k,\sigma}\, f_{2,k,\sigma})\,, \tag{4}$$

where $f^\dagger_{i,k,\sigma}$ ($f_{i,k,\sigma}$) are the creation (annihilation) operators of the localized electrons in the sub-lattice i ($\equiv$ 1,2) and ϵ_f is the dispersionless and the renormalized energy of the localized levels. For simplicity of the claculation the renormalized ϵ_f is assumed to lie exactly on the Fermi level $\epsilon_F = 0$. The intersite *f*-electron hopping in real space is described by the Hamiltonian $\mathcal{H}_f^2$ as

$$\mathcal{H}_f^2 = -\sum_{i,k,\sigma} e_{ij}\,(f^\dagger_{1,i,\sigma}\ f_{2,j,\sigma} + h.c)\,, \tag{5}$$

where $f^\dagger_{1,i,\sigma}$ and $f^\dagger_{2,j,\sigma}$ are the creation operators of the *f*-electrons at two different sub-lattices 1 and 2 respectively with spin σ. The e_{ij} is the nearest neighbour *f*-electron hopping matrix element. The Fourier transformed *f*-electron hopping Hamiltonian is given by

$$\mathcal{H}_f^2 = \sum_{k,\sigma} E_0(k)(f^\dagger_{1,k,\sigma}\, f_{2,k,\sigma} + f^\dagger_{2,k,\sigma}\, f_{2,k,\sigma})\,, \tag{6}$$

where $E_0(k)$ gives the narrow dispersion of the *f*-electron band. The sub-lattice magnetization due to the *f*-electron lattice arise from the Heisenberg exchange interaction between the magnetic moments at neighbouring sites. Within

the mean field approximation the Hamiltonian $\mathcal{H}_h$ for the staggered sub-lattice magnetization can be written as

$$\mathcal{H}_h = (h/2)\sum_{k,\sigma}(f^{\dagger}_{1,k,\sigma} f_{1,k,\sigma} - f^{\dagger}_{2,k,\sigma} f_{2,k,\sigma}), \quad (7)$$

where h is the strength of the sub-lattice magnetization which stimulates AFM correlation of the f-electrons. The Hamiltonian $\mathcal{H}_v$ describing the hybridization is given by

$$\mathcal{H}_v = V\sum_{k,\sigma}(c^{\dagger}_{1,k,\sigma} f_{1,k,\sigma} + c^{\dagger}_{2,k,\sigma} f_{2,k,\sigma} + h.c), \quad (8)$$

where the strength of hybridization (V) is wave vector and spin independent. It should be noted that only the on-site hybridization is induced *i.e.* the localized electron belonging to the sub-lattice 1 hybridizes with the conduction electrons of that sub-lattice alone, and so on. The strong onsite Coulomb correlation in these systems which mainly accounts for its heavy fermion behaviour is given by

$$\mathcal{H}_I = U_f\sum_{i,j}(n^f_{1,i,\uparrow} n^f_{1,i,\downarrow} + n^f_{2,j,\uparrow} n^f_{2,j,\downarrow}), \quad (9)$$

where U_f is the Coulomb correlation energy of the f-electrons at sub-lattices 1 and 2. The heavy fermion superconductors UM_2Al_3 (M = Pd, Ni) are unconventional anisotropic superconductors, probably d-wave. In addition, there is some evidence that the superconductivity is mediated by antiferromagnetic spin-fluctuations [15]. However, we consider the mean field BCS Hamiltonian describing phonon mediated superconductivity is given by

$$\mathcal{H}_s = -\Delta\sum(c^{\dagger}_{1,k\uparrow}c^{\dagger}_{1,-k\downarrow} + c^{\dagger}_{2,k\uparrow}c^{\dagger}_{2,-k\downarrow} + h.c.), \quad (10)$$

where

$$\Delta_k = -\sum\tilde{V}_k(< c^{\dagger}_{1k\uparrow}c^{\dagger}_{1-k\downarrow} > + < c^{\dagger}_{2k\uparrow}c^{\dagger}_{2-k\downarrow} >), \quad (11)$$

where only intra sub-lattice pairing is assumed and Δ is the wave vector independent s-wave superconducting order parameter. It may be noted that the total Hamiltonian of the system is a mean field one and hence can be solved exactly either by appropriate diagonalization using the Bogoliubov transformation or by writing the equations of motion for the single particle Greens function [16]. The later procedure has been followed to solve for the Greens functions and to calculate the appropriate single particle correlation functions which in turn determines the order parameters corresponding to the AFM and SC long range orders.

4. Calculation of electron Green's functions

We calculate the one electron Green functions using the Hamiltonian $\mathcal{H}$ given in eq. (1) for the superconducting state of the HF system. The double time electron Green functions of Zubarev type [16] are calculated by equations of motion method. The Green functions $A_i(k,\omega)$, $B_i(k,\omega)$, $E_i(k,\omega)$, $F_i(k,\omega)$, $G_i(k,\omega)$, and $H_i(k,\omega)$, (with i = 1–8) are the coupled set which are involved in the calculation. Finally the SC gap and magnetic order parameters are calculated by using the Green's functions defined below in eq. (12).

$$A_2(k,\omega) = << c^{\dagger}_{1,-k\downarrow}; c^{\dagger}_{1,k\uparrow} >>_{\omega},$$

$$B_2(k,\omega) = << c^{\dagger}_{2,-k\downarrow}; c^{\dagger}_{2,k\uparrow} >>_{\omega},$$

$$E_1(k,\omega) = << f_{1,k\uparrow}; f^{\dagger}_{1,k\uparrow} >>_{\omega},$$

$$F_1(k,\omega) = << f_{1,k\downarrow}; f^{\dagger}_{1,k\downarrow} >>_{\omega},$$

$$G_1(k,\omega) = << f_{2,k\uparrow}; f^{\dagger}_{2,k\uparrow} >>_{\omega},$$

$$H_1(k,\omega) = << f^{\dagger}_{2,k\downarrow}; f^{\dagger}_{2,k\downarrow} >>_{\omega}. \quad (12)$$

The coupled equations are solved to find out the Green's functions defined in eq. (12) (dropping the functional dependences *i.e.* (k,ω) for simplicity).

$$A_2 = \frac{1}{4\pi}\left[\frac{(\omega-\Delta)(\omega^2-\tilde{\epsilon}_f^2) - V^2(\omega - h/2)}{|D_1(\omega)|} - \frac{(\omega+\Delta)(\omega^2-\tilde{\epsilon}_f^2) - V^2(\omega-h/2)}{|D_2(\omega)|}\right] \quad (13)$$

where

$$|D_{1,2}(\omega)| = (\omega^2 - E_k^2)(\omega^2 - \tilde{\epsilon}_f^2) - 2V^2\{\omega^2 \mp \Delta h/2 + E_0(k)\epsilon_k\} + V^4$$

$$= \omega^4 - R\omega^2 + S_{1,2} \quad (14)$$

with

$$R = E_k^2 + \tilde{\epsilon}_f^2 + 2V^2,$$

$$S_{1,2} = E_k^2\,\tilde{\epsilon}_f^2 \pm \Delta h V^2 - 2\epsilon_k E_0(k)V^2 + V^4,$$

$$E_k^2 = \epsilon^2 + \Delta^2,$$

$$\tilde{\epsilon}_f^2 \quad E_0^2(k) + h^2/4. \tag{15}$$

The poles of the Green's functions given in eqs. (13) give eight quasi-particle energy bands $\pm\omega_i$ (i = 1 to 4).

5. Expressions for SC and AFM gaps

We have used here a phonon mediated B.C.S. type of Cooper pairing between conduction electrons. The expression for energy gap parameter (Δ) for intra-sublattice pairing can be calculated from the Green functions $A_2(k,\omega)$ and $B_2(k,\omega)$ given in eq. (12) respectively. The superconducting gap is defined as

$$\Delta_k = -\sum \tilde{V}_k [< c^\dagger_{1,k\uparrow} c^\dagger_{1,-k\downarrow} \quad c^\dagger_{2,k\uparrow} {}_{2,-k\downarrow} >], \tag{16}$$

$\tilde{V}_k$ being the strength of the attractive interaction between the two electrons mediated by the phonons. We have a limitation on the k-sum owing to the restriction that the attractive interaction is only effective with energy $|\epsilon_1 - \epsilon_2| < \omega_D$. Here, the attractive interactions between two carriers are ϵ_1 and ϵ_2 to form the Cooper pairs and ω_D is the Debye frequency. Further, we adopt the following simplified form for the interaction potential $\tilde{V}_k$ in the ordinary isotropic weak coupling limit. Here $\tilde{V}_k = -V_o$, if $|\epsilon_1 - \epsilon_2| < \omega_D$, $\tilde{V}_k = 0$, otherwise. In this approximation we assume that the gap parameter is independent of k. The superconductivity in UPd_2Al_3 is believed to be anisotropic and unconventional. However, we can observe some important features of interplay of SC and AFM from this simplified eq. (16). The final expression for superconducting energy gap is

$$\Delta(T) = \frac{V_0 N(0)}{4} \int_{-\omega_D}^{\omega_D} d\epsilon_k \left[\frac{F_{11} - F_{21}}{\omega_1^2 - \omega_2^2} + \frac{F_{31} - F_{41}}{\omega_3^2 - \omega_4^2} \right], \tag{17}$$

where

$$F_{i1} = K_i \tanh(\beta\omega_i/2), \tag{18}$$

$$K_1 = \frac{2\Delta(\omega_1^2 - \tilde{\epsilon}_f^2) - hV^2}{\omega_1},$$

$$K_2 = \frac{2\Delta(\omega_2^2 - \tilde{\epsilon}_f^2) - hV^2}{\omega_2},$$

$$K_3 = \frac{2\Delta(\omega_3^2 - \tilde{\epsilon}_f^2) + hV^2}{\omega_3},$$

$$K_4 = \frac{2\Delta(\omega_4^2 - \tilde{\epsilon}_f^2) + hV^2}{\omega_4} \tag{19}$$

with i = 1–4. $N(0)$ is the density of states of the conduction band at the Fermi level. We replace $\sum_k$ by $\int N(0)\, d\epsilon_k$ with integration limit form $-\omega_D$ to $+\omega_D$. We have introduce the staggered magnetic field on uranium sites to break the spin symmetry in the f-electrons. The AFM order parameter h in f-electrons is defined as

$$h = -\frac{1}{2} g_L \mu_B \sum_{k,\sigma} \sigma [< f^\dagger_{1,k,\sigma} f_{1,k,\sigma} > - < f^\dagger_{2,k,\sigma} f_{2,k\sigma} >], \tag{20}$$

where g_L and μ_B are Lande g-factor and Bohr magnetron respectively. The correlation functions $< f^\dagger_{1,k,\uparrow} f_{1,k,\uparrow} >$ and $< f^\dagger_{1,k,\downarrow} f_{1,k,\downarrow} >$ are calculated from the Green functions $E_1(k,\omega)$ and $F_1(k,\omega)$. Similarly the correlation functions $< f^\dagger_{2,k,\uparrow} f_{2,k,\uparrow} >$ and $< f^\dagger_{2,k,\downarrow} f_{2,k,\downarrow} >$ are calculated from the Green functions $G_1(k,\omega)$ and $H_1(k,\omega)$. The final expression for the staggered magnetic field is given by

$$h = \frac{g_2}{4} \int_{-W/2}^{+W/2} d\epsilon_k \left[\frac{E_{11} - E_{21}}{\omega_1^2 - \omega_2^2} + \frac{E_{31} - E_{41}}{\omega_3^2 - \omega_4^2} \right], \tag{21}$$

where

$$E_{i1} = E_i \tanh(\beta\omega_i/2); \tag{22}$$

$$E_1 = \frac{h(\omega_1^2 - E_k^2) - 2\Delta V^2}{\omega_1},$$

$$E_2 = \frac{h(\omega_2^2 - E_k^2) - 2\Delta V^2}{\omega_2},$$

$$E_3 = \frac{h(\omega_3^2 - E_k^2) + 2\Delta V^2}{\omega_3},$$

$$E_4 = \frac{h(\omega_4^2 - E_k^2) + 2\Delta V^2}{\omega_4} \tag{23}$$

with i = 1–4. W is the band width of the f-electron and g_2 = $g_L \mu_B N_f(0)$. The $\sum_k \rightarrow \int N_f(0)\, d\epsilon_k$ where $N_f(0)$ is the density of states of the f-electron band near the Fermi level. The eqs. (17) and (21) form a coupled set of equations for the two order parameters $\Delta(T)$ and $h(T)$ which are to be determind self consistently to study their temperature

dependence and mutual interplay. All the quantities entering in eqs. (17) and (21) are made dimensionless by dividing them by Debye energy ω_D. Thus, the dimensionless order parameters are defined as $\Delta(T)/\omega_D = z$ and $h/\omega_D = h$, the variables as $\epsilon_k/\omega_D = x$, $k_BT/\omega_D = t$, $V/\omega_D = V$. The dimensionless coupling constants are $N(0)V_0 = g_1$ and $g_L\mu_B N_f(0) = g_2$.

6. Results and discussion

The interplay of superconductivity (SC) and antiferromagnetism (AFM) in the heavy fermion (HF) systems UM_2Al_3 can be studied by varying different model parameters of the electronic sub-system. These parameters are the SC gap z, AFM gap h, SC coupling constant g_1, AFM coupling constant g_2, the hybridization parameter (v) between the conduction and f-electrons, temperature t. The position of f-electron energy level assumed to lie on the fermi level ϵ_F under the half filling band situation.

The temperature variation of SC gap z, AFM gap are shown in Figure 1 before interplay. They are calculated numerically and self-consistently with an accuracy of 10^{-4}. The SC plot gives a SC gap z (t = 0) = 0.0077 and transition temperature t_c = 0.0025 corresponding to universal constant $\Delta(0)/k_BT$ = 3.08 as against BCS value 1.76. The corresponding SC coupling constant g_1 = 0.09916. Similarly the AFM plot gives a Néel temperature t_N = 0.0014 corresponding to an AFM coupling g_2 = 0.18822. These parameters are fixed for $t_c > t_N$ befor interplay between SC and AFM.

When these two order parameters interplay the self-consistent plot is show in Figure 2. As compared to their values before interplay it is observed that the SC transition temperature t_c is suppressed considerably by AFM to nearly one-third of its value. The SC gap also suppressed considerably to nearly one-third of its value giving rise to

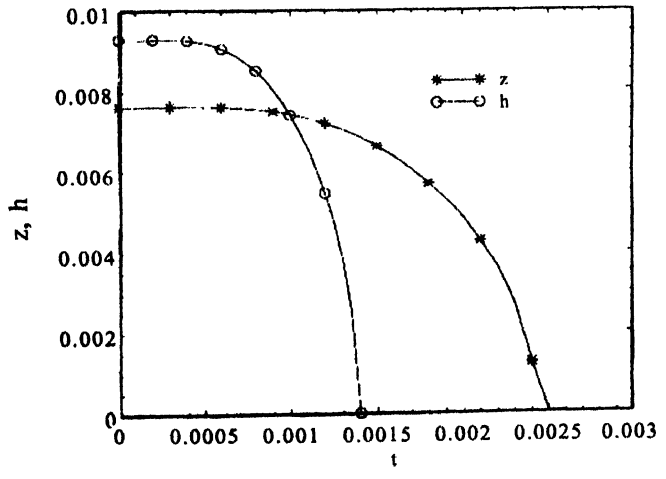

Figure 1. Individual plots of z *vs* t for h = 0, v = 0.02, g_1 = 0.09916 and plot of h *vs* t for z = 0, v = 0.02 and g_2 = 0.18822.

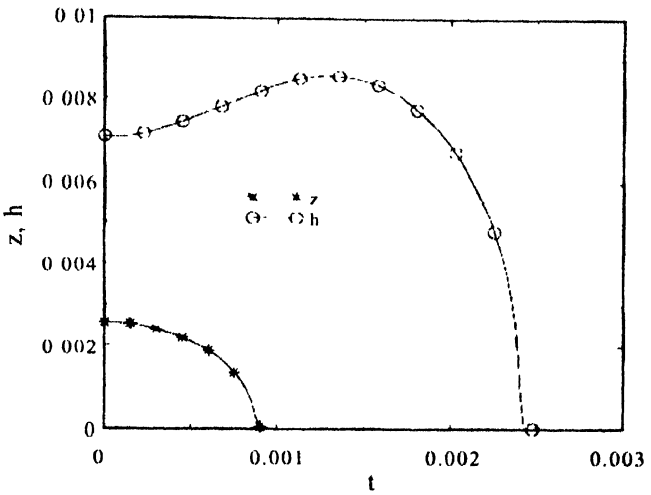

Figure 2. Self consistent plots of z *vs* t and h *vs* t with fixed values of v = 0 02, g_1 = 0.09916 and g_2 = 0 18822

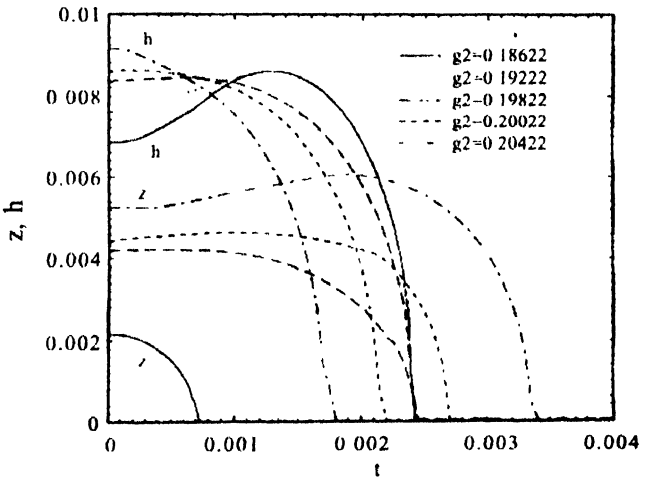

Figure 3. Self consistent plots of z *vs* t and h *vs* t with fixed values of v = 0.02 and g_1 = 0 09916 for different values of g_2 = 0.18622, 0.19222, 0.19822, 0 20022 and 0.20422.

the BCS universal value $\Delta(0)/k_BT \approx 2.94$. But the AFM Néel temperature t_N is enhanced to double its value by superconductivity. The AFM staggered field $h(T = 0)$ is suppressed a little from $h(0)$ = 0.0094 to 0.0075. Again the t_c and t_N values are nearly in conformity with experimental observation : *i.e.* $t_N > t_c$. The experiment gives T_N = 4.5 K and T_c = 1 K for UNi_2Al_3 system [2], and T_N = 14.5 K and $T_c = 2K$ for UPd_2Al_3 [3]. Neutron scattering experiments [7,8] shows that the observed magnetic peak intensities increase continiuously from the Néel temperature T_N down

to T_c. Below T_c, the magnetic peak intensities turn to decrease with decreasing the sample temperature. They confirmed that the suppression of the magnetic intensities is due to superconductivity. This behaviour can be understood in terms of the coupling between magnetic and superconducting order parameter as given in the present model. It is conclude that the coupling of the magnetic and superconducting order parameters would be a characteristic feature in the heavy fermion superconductors.

The effect of the AFM coupling g_2 on the SC gap (see lower panel) and the AFM gap (see upper panel) is shown in Figure 3. It unambiguously displays the strong correlation between the superconductivity and antiferromagnetism. The increase of the AFM coupling g_2 enhances the SC order parameter (lower panel) throughout the temperature range and the SC transition temperature (from t_c = 0.00085 to 0.0035 lower panel). It is interesting to note that the increase of g_2 from 0.18622 to 0.20422 reduces the BCS universal constant from $\Delta(0)/k_BT$ = 2.94 to a value of $\approx$ 2.08 indicating a considerable superssion the SC gap at low temperature where the AFM order (see upper panel) is stronger than the SC gap. The effect of the AFM coupling g_2 on its own staggered field is still more interesting. It is well known that the AFM coupling g_2 should enhance the magnitude of the staggered field h as well as the Néel temperature t_N. However the interplay between the SC and AFM exhibits some anomalies in the staggered field h (upper panel) when the AFM coupling g_2 increases gradually. For lower values of the AFM coupling (g_2 < 0.19222), the Néel temperature remains unaltered indicating its sharpness and robustness. However the staggered field strength h increases at low temperatures with increase of the AFM coupling (which is commonly anticipated). In this low temperature range (t <0.0015), both the order parameters z and h are enhanced with increase of the AFM coupling g_2 even though suppression in the low temperature range is obvious in both the order parameters due to their mutual interaction. In conclusion, we can say that present model can explain the strong coupling between the magnetism and superconductivity.

Acknowledgments

Two of the authors (MSO, GCR) would like to gracefully acknowledge the research facilities of the Institute of Physics, Bhubaneswar, available to them during their short stay.

References

[1] N Grewe and F Steglich *Hand Book on the Physics and Chemistry of Rare Earths* **vol. 14** (eds.) K A Gschneidner (Jr.) and L. Eyring, (Amsterdam : North-Holland) p343 (1991)

[2] C Geibel *Z. Phys.* **B83** 305 (1991)

[3] C Geibel, C Schank, S Thies, H Kitazawa, C D Bredl, A Böhm, M Rau, A Grauel, R Caspary, R Helfrich, U Ahlheim, G Weber and F Steglich *Z. Phys.* **B84** 1 (1991)

[4] G Aeppli, D Bishop, C Broholm, E Bucher, K Siemensmeyer, M Steiner and N Stüsser *Phys. Rev. Lett.* **63** 676 (1989)

[5] C Broholm, J K Kjems, W J L Buyers, P Matthews, T T M Palstra, A A Menovsky and J A Mydesh *Phys. Rev. Lett.* **58** 1467 (1987)

[6] A Krimmel, P Fischer, B Rossli, H Maletta, C Geibel, C Schank, A Grauel, A Loidl and F Steglich *Z Phys.* **B86** 161 (1992), *Solid State Commun.* **87** 829 (1993); H Kita *et al J. Phys. Soc Jpn.* **63** 726 (1994)

[7] N K Sato, N Aso, K Miyake, R Shilina, P Thalmeier, G Varelogiannis, C Geibel, F Steglich, P Fulde and T Komatsubara *Nature* **410** 340 (2001)

[8] N Metoki, Y Haga, Y Koike and Y Onuki *Phys. Rev. Lett.* **80** 5417 (1998)

[9] M Jourdan, M Huth, J Hessert and H Adrian *Physica* **B230** 232 (1997)

[10] M Kyogaku, Y Kitaoka, K Asayama, C Geibel, C Schank and F Steglich *J. Phys. Soc. Jpn.* **61** 2660 (1992)

[11] G C Rout and S Das *Physica* **C339** 17 (2000)

[12] G C Rout, S Das and S N Behera *Physica* **C371** 185 (2002)

[13] K Harigaya *J. Phys. : Condens. Matter* **1** 10459 (1989)

[14] G C Rout, M S Ojha and S N Behera (to be published)

[15] M Jourdan, M Huth and H Adrian *Nature* **398** 47 (1999)

[16] D N Zubarev *Sov. Phys. Usp.* **3** 320 (1960)